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MATERIALS TECHNOLOGY SECTION
A REVIEW OF 1990 AND PROPOSALS FOR 1991

Report No. 91-151-K

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ABSTRACT

The programs performed in 1990 in the Materials Technology Section are reviewed. The Section is involved in five main areas of research: Pressure Tube Deformation; Development and Application of Specialized Techniques for Mechanical and Physical Property Measurement; Pressure Tube Fabrication; Advanced Industrial Materials and Analysis of Service Failures.

The highlights of the 1990 progress in these areas is documented and the proposed 1991 studies are outlined.

job	file	date	report no.
84-875-0200	823	July 5, 1991	91-151-K

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EXECUTIVE SUMMARY

MATERIALS TECHNOLOGY SECTION: A REVIEW OF 1990 AND PROPOSALS FOR 1991

R.G. Fleck
Materials Technology Section
Metallurgical Research Department

The Materials Technology Section performs programs in the areas of: Pressure Tube Deformation, Pressure Tube Fabrication, Development and Application of Specialized Techniques for Mechanical and Physical Property Measurement and Advanced Industrial Materials.

Detailed transmission electron microscopy to determine the effects of neutron irradiation on the microstructure of pressure tube alloys is performed in support of the pressure tube deformation program. The materials examined have been irradiated in CANDU reactors and in test reactors. The structures formed in the different irradiation facilities appear to be similar. The important aspects of the work relate to the extent of damage that forms small dislocation loops and the segregation of impurities. Irradiation growth data from the Osiris reactor show general agreement with results obtained from the irradiations in Dido. The Osiris tests also include small pressurized creep capsules with a metallurgical structure similar to that of pressure tubes. To model the deformation behaviour of fuel channels the code CDEPTH was upgraded. The program can now be used with SLAR to identify "on-line" the new locations for the spacers.

Pressure tube fabrication studies concentrate on the parameters that control the cold draw process to eliminate shear crack formation. A modified die design has been used to cold draw TG3- R1 pressure tubes to the second stage of a three stage reduction.

In the area of Specialized studies the differential scanning calorimetery technique was used to measure the total hydrogen concentrations in scrape samples removed from Pickering 4 and Bruce 1. The technique has proved a useful addition to the capabilities to characterize materials removed from power reactors. The biaxial deformation behaviour of fuel cladding exposed to steam was shown to be different to that observed in air. The indications are that hydrogen uptake in the cladding impacts on the kinetics of deformation.

A technique to connect high temperature super conductors to the electric power system was developed. Components of the transmission/distribution system are being evaluated to establish if new materials would improve their performance.

A variety of failure analyses were performed throughout the year.

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TO: Dr. D. Mills
Director of Research

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MATERIALS TECHNOLOGY SECTION
A REVIEW OF 1990 AND PROPOSALS FOR 1991

1.0 *INTRODUCTION*

This annual status report is designed to provide the reader with a rapid overview of the work program being carried out in the Materials Technology Section of the Metallurgical Research Department. The current structure of this section resulted from a reorganization of the Metallurgical Research Department. This has added responsibilities for Advanced Industrial Materials (AIM) to the work of what was the Materials Integrity Section while, at the same time, removing much of the responsibility for pressure tube fracture work.

The program of this section is varied but the overall goal of the section can be stated simply as "improvement of the long term reliability of materials used in the power system through the development and dissemination of the understanding and use of the material structure - property relationships". This leads to projects as diverse as irradiation of pressure tube materials in test reactors in France to identification of new materials for transmission and distribution line hardware. Currently, there are five major areas of effort:

1. Pressure Tube Deformation
2. Development and Application of Specialized Techniques for Mechanical and Physical Property Measurement.
3. Pressure Tube Fabrication
4. Advanced Industrial Materials
5. Analysis of Service Failures (Distributed throughout the Metallurgical Research Department)

The work in these areas is a combination of experiment, analysis and modelling to meet (in most cases) some specific targets. Some of these targets are short term and directly supportive of other operations (e.g. modelling of SLAR - Spacer Location and Repositioning in Fuel Channels), whereas others are ongoing, very long term projects (understanding pressure tube deformation).

For most of the work done on pressure tubes, we work in close cooperation with AECL and other Utilities through the CANDU Owners Group (COG). The Canadian Electrical Association (CEA) supports some of the other work. This report reviews some of the key results which have been obtained in the above program areas in the past year and indicates the direction for work in the coming period.

2.0 *MATERIALS TECHNOLOGY SECTION PERSONNEL*

R.G.	Fleck	Supervising Engineer
L.J.	Compton	Section Assistant

Irradiation Deformation

N.	Badie	Engineer (three months)
A.	Donner	Technologist
J.	Elder	Engineer
Z.	Grozdanovski	Technician
E.T.C.	Ho	Engineer
R.A.	Holt	Engineer (five months)
R.	Jarochowicz	Technician
M.J.	McGraw	Technologist
A.	McMillan	Technician
D.	Oad	Technician
S.	Perkons	Engineer
V.	Perovic	Engineer
K.	Tashiro	Engineer

Advanced Industrial Materials

G.	Bellamy	Engineer
J.O.	Noga	Engineer
P.	Mayer	Engineer
T.	Ryans	Technician

Summer Students

K. Linfield
D. LeFrancois
J. Pringle

3.0 *IRRADIATION DAMAGE AND DEFORMATION STUDIES*

3.1 *Microstructural Studies*
(V. Perovic, R. Jarochowicz)

Transmission electron microscopy was extensively employed during 1990 in studying the microstructural and microchemical characterization of neutron irradiated Zr-Nb alloys.

3.1.1 *Microstructural/Microchemical Development in Neutron Irradiated Zr-Nb Alloys*

The results presented in this study clearly demonstrate the complexity of the microstructure developed after neutron irradiation. The <a>-type defects are revealed as a very high density of black/white spots or dislocation network-like contrast. The microstructure of all materials studied (surveillance pressure tubes, various growth and TEM specimens) was remarkably similar. There is a strong indication that a large fraction of the <a> contrast which is thought to be caused by small dislocation loops or dislocation networks might in fact be associated with the epitaxial oxide particles on the free surfaces. This in turn suggests that in fine grained (<1 μm) Zr-Nb alloys the α-α sub-boundaries and α-β interfaces could act as very effective sinks for the irradiation induced point defects.

A relatively high density of <c>-component dislocations has also been observed. These dislocations tend to align in rows throughout the entire grains in some alloys. The <c>-component dislocations were always associated with the α-β interfaces and α-α sub-boundaries. This strongly indicates that they are formed to accommodate intergranular constraints generated by irradiation growth.

Microchemical studies concentrated on iron segregation. In unirradiated Zr-Nb alloy where the retained β_{Zr}-phase (<20% Nb) is still untransformed and continuous the iron was almost completely dissolved in the β_{Zr}-phase. In all EDX spectra taken from the α_{Zr}-matrix the iron signal was absent or below the limit of detectability. The second set of results is irradiated TG3.R1 alloy where the retained β_{Zr}-phase is transformed to the β'_{Nb}-phase (60-80% Nb), the EDX spectras have shown that both β'_{Nb}-phase and α_{Zr}-matrix were free of iron. However, a very strong iron signal was always observed when the spectra were taken from the α-α sub-boundaries clearly demonstrating iron segregation.

3.1.2 *C-Component Dislocations in Sub-Boundaries in a Zr-2.5 Wt% Nb Alloy*

The character of α-α sub-boundaries is thought to be established by the extrusion operation. The boundaries are composed of <a> and <c> dislocations forming a variety of tilt, twist and mixed boundaries. The α-α boundaries are closely linked with the α-β interface structure in extruded or β-quenched alloys and are only formed during dissolution of the β particles. Rotation of <a>-tilt boundaries is localized around <c> dislocations forming a step structure. The configuration of <c>-dislocation steps is believed to be fault bounded by two 1/2 <c> partial dislocations. The importance of these dislocation arrays in understanding the strengthening mechanisms and irradiation growth behaviour of the alloy is emphasized.

3.1.3 *Hydride Precipitation*

The study on the role of residual grain-interaction stress on hydride precipitation in coarse-grained Zircaloy-2 was completed.

Heterogeneous nucleation of hydrides at grain boundaries or twin boundaries was commonly found in samples subjected to 4% prior deformation, while transgranular hydrides were most frequently observed after a prior 0.3-0.5% compressive deformation or annealing. The local stress state at grain boundary facets or twins is thought to be the deciding factor in determining where hydrides nucleate and low hydride stacks form.

3.2 *Irradiation Programs*

3.2.1 *High Fluence Deformation of Pressure Tubes*
(J. Elder, R.A. Holt, A. McMillan)

Osiris Program (Cooperative project with CRNL)

Trillium 2 -

In the Trillium 2 insert, 42 growth specimens, 7 creep capsules and 6 specimens for transmission electron microscopy are being irradiated at a temperature of 280°C. Table 1 gives the irradiation history for the insert and the irradiation schedule until April/92. The insert is presently in Osiris for Phase 3. At the end of phase 2 the total accumulated peak fluence for the insert was 2.39×10^{25} n/m^2.

TABLE 1
TRILLIUM 2 IRRADIATION HISTORY AND SCHEDULE

PHASE	*NO. OF CYCLES*	*START DATE*	*FINISH DATE*	*FLUENCE* n/m^2
1	4	April/89	September/89	1.05×10^{25}
2	5	November/89	June/90	1.34×10^{25}
3	4	September/90	June/91	
4	8	July/91	July/92	

Table 2 indicates the number of growth and creep specimens from each material which were included in the insert during phase 1, 2 and 3. Periodic changes of specimens have occurred. The five creep capsules, with fuel cladding texture, were replaced with capsules with pressure tube textures.

During phase 1 and 2, consistent variations in temperature from 280°C have been observed with the thermocouples in tiers 3 and 5. Of particular concern is that average temperatures in tiers is only 262°C. There is presently no viable solution for eliminating these temperature deviations.

Figures 1 and 2 compare the growth results from the Trillium 2 experiment with growth behaviour previously established in Dido. The longitudinal growth rate of the reference material (#8), Zircaloy-2, SGHWR, tube 002, continues to appear slightly higher for Osiris than for Dido. The growth rates exhibited by materials 1 (Darlington tube H190M) and 2 (Task Group 3 Route 1 tube TG040M) in Osiris are consistent with the long term growth rates exhibited in Dido. The transverse growth strains from Dido are within the specimen to specimen variation in Osiris.

Figure 3 illustrates the measurement results for the creep capsules after phase 1 and phase 2 of irradiation. Comparing the results from phase 1 and phase 2, there does not appear to be any transient behaviour in the diametral strains. However, the axial strains appear to have exhibited a transient in the early period of irradiation.

Trillium 3 -

In the Trillium 3 insert, 42 growth specimens, 7 creep capsules and 6 specimens for TEM are to be irradiated at 310°C. Table 2 indicates the number of growth and creep specimens from each of the 17 experimental materials which are to be included in the insert for phase 1. Eight of the 42 growth specimens are preirradiated growth specimens from the Dido experiment.

DIDO Program

Results from the Dido reactor have shown a large effect of metallurgical structure on the growth rate, and a significant disagreement with current models for in reactor deformation of pressure tubes. The most recent results from Dido could be interpreted to indicate a continuous increase in the growth rate.

The irradiation growth program in the Dido reactor at Harwell has been brought to an end after 12 years when the reactor was permanently shut down on March 31, 1990.

TABLE 2

Trillium 2 and 3 Specimen Materials List

A. GROWTH SPECIMENS

MATERIAL DESCRIPTION	Trillium 2 Phase 1	2	3	4	Trillium 3
1. Darlington, tube H190M (115")	8	7	7	6	6
2. OH Task Group 3 (TG3) Route-1, tube TG04M (138-144")	8	7	6	6	6
3. Pt. LePreau tube E064 (4.25")	8	7	7	6	6
4. Pickering A, tube 601	8	7	6	6	3
5. Low Fe, beta-quenched					
a. tube D562 (400ppm Fe)	1	1	1	1	2
b. tube D866 (Pickering 8, N9E-25",393ppm Fe)	1	1	1	1	2
6. High Fe, beta-quenched					
a. tube G710 (1060 ppm)	1	1	1	1	1
b. tube D1170B (1000 ppm)	1	1	1	1	2
7. Non beta-quenched					
a. tube C363 (Pickering 8,H13b,437 ppm Fe)	1	1	1	1	1
b. tube D93B (616 ppm Fe)	1	1	1	1	1
8. SGHW, Zircaloy-2 tube 002	4	3	3	-	-
9. B2P12, tube 939, machined from a pre-irradiated section (265 cm)	-	3	3	3	-
10. Pilgered tube T007, back end	-	2	2	2	2
11. OH Task Group 3 (TG3) Route 1, tube J12-CA-84 (same as DIDO)	-	-	2	2	-
12. As-received material (AR) pre-irradiated in DIDO	-	-	-	2	-
13. SGHW tube pre-irradiated	-	-	-	3	-
14. Task Group 3 Route 1 (R1), tube J12CA pre-irradiated in DIDO	-	-	-	-	4
15. Darlington, tube H190M pre-irradiated in DIDO	-	-	-	-	4
16. G1175 a. front end b. back end	-	-	-	-	2
17. Task Group 3 Route 4 Tube 15					
a. as extruded	-	-	-	-	-
b. 6 hours at 500°C	-	-	-	-	-

B. CREEP CAPSULES

MATERIAL DESCRIPTION	Trillium 2 Phase 1	2	3	4	Trillium 3
Zr-2.5%Nb Fuel Cladding	7	7	2	2	2
Micro-Pressure Tube Material	-	-	5	5	5

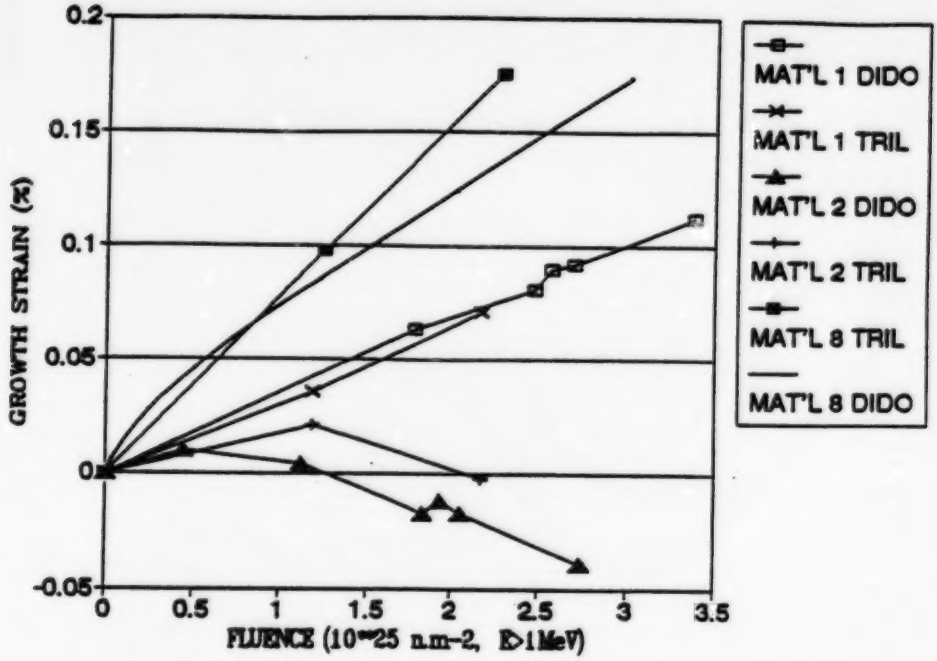


Figure 1 Longitudinal growth strain results from the Trillium 2 experiment compared with results from the Dido experiment.

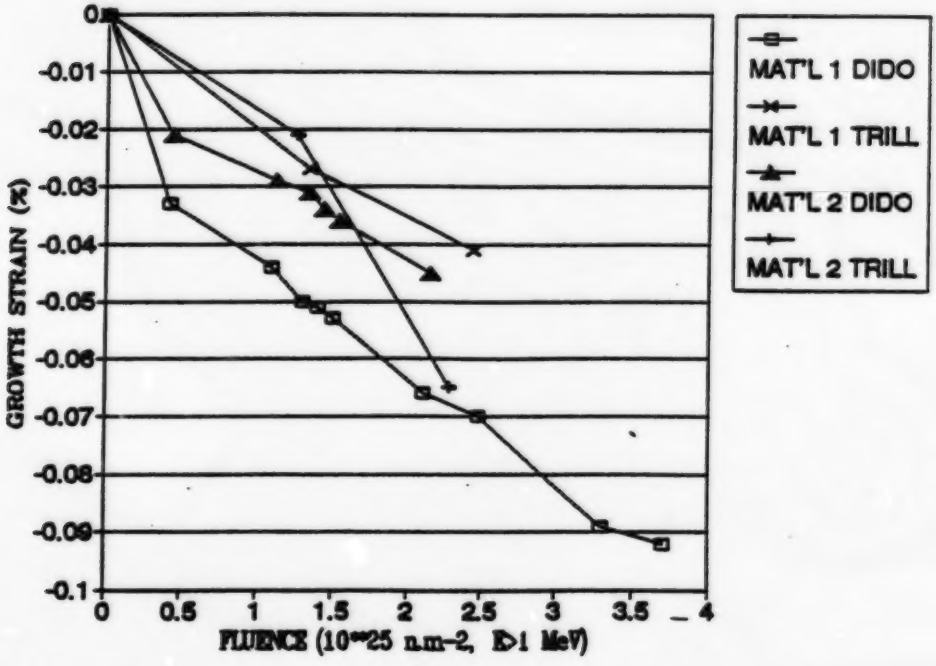


Figure 2 Transverse growth strain results from the Trillium 2 experiment compared with results from the Dido experiment.

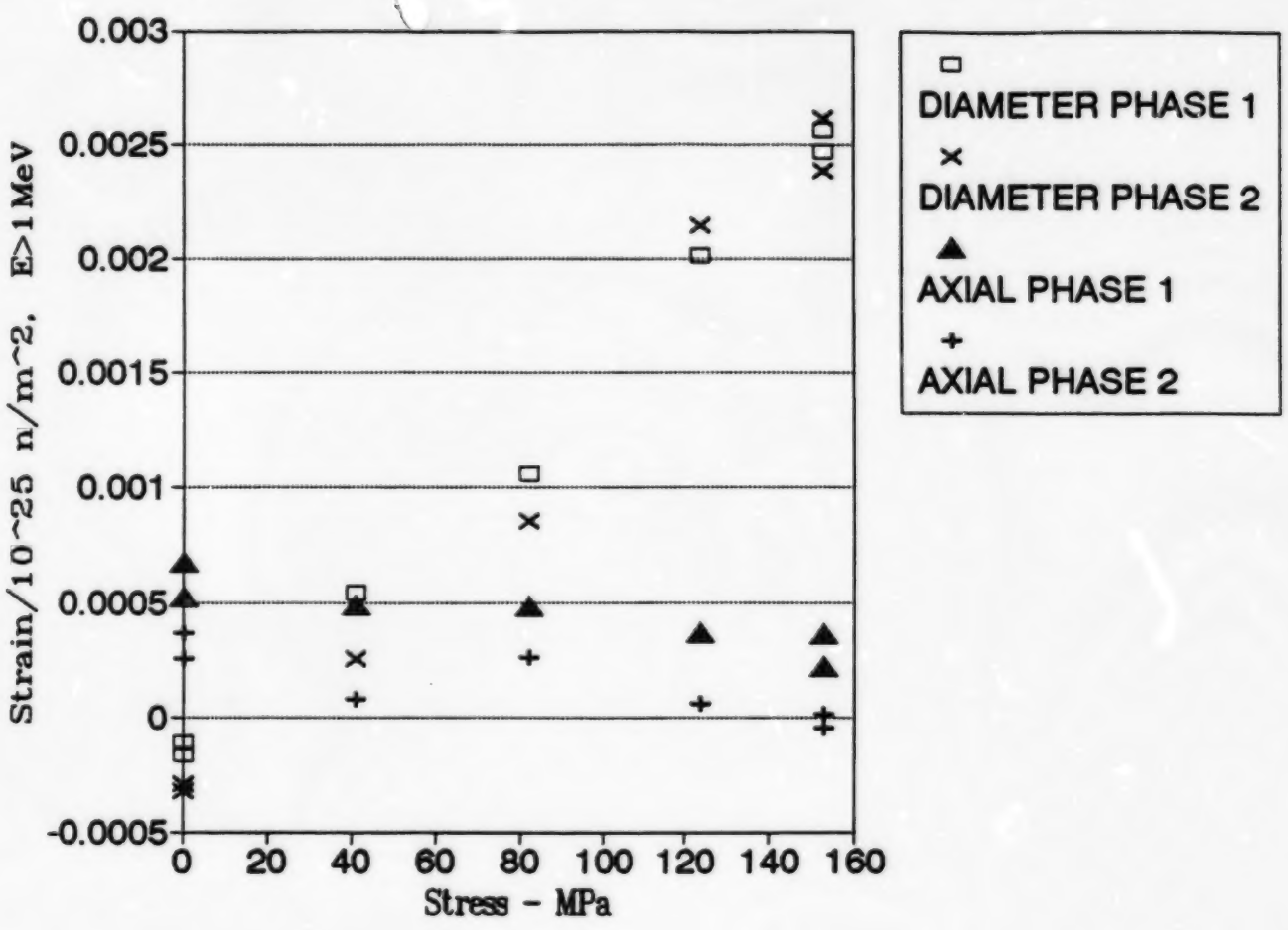


Figure 3 Diametral and axial creep strain results for the Trillium 2 creep capsules after the first and second phase of irradiation.

3.2.2 *Evaluation of Power Reactor Fast Fluxes*

(Cooperative program with CRNL)
(J. Elder, N. Badie)

In this program transmutation and displacement damage monitors along with creep, growth and mechanical test specimens of pressure tube materials are being irradiated in one or two special dummy elements in the outer element positions of carrier bundles. The objective is to obtain quantitative correlations between the fast fluxes experienced by power reactor components and by small specimens exposed in test reactors. The fast fluences (E>1 MeV) measured from the monitors agreed well with those calculated from bundle powers. The results also showed that the effective damage cross sections for fast neutrons (E>1 MeV) are comparable in Osiris and in a CANDU pressure tube (i.e. 1450-1520 vs 1280-1530 barn.dpa(Zr)/n).

3.3 *Analysis of In-Service Deformation Behaviour of Fuel Channels*

3.3.1 *Materials Characterization*

(J. Elder)

Defects (dislocations) and internal stresses are generated in pressure tubes during the fabrication process. The number of dislocations and the magnitude of the internal stresses in the atomic lattice of pressure tubes have a large effect on their in-reactor stability. X-ray diffraction (XRD) line broadening and lattice parameter measurement can be used to estimate dislocation density and assess internal stresses in zirconium alloy pressure tubes.

A computer program which gives the dislocation density in a specimen from an analysis of the X-ray diffraction line broadening has been improved and altered to run on a 80386 personal computer.

3.4 *Modelling*

3.4.1 *CDEPTH and PRECD*

(N. Badie, R. Sauve and K. Linfield)

CDEPTH V6.2 (386 Version) and its utility programs have been distributed to all COG members, and are now installed at 8 sites, as shown in Table 3. The maintenance and support of CDEPTH on all these systems has been a major effort during 1990.

Several modifications were made to CDEPTH in order to allow multiple runs to be specified in one input file, and to ensure compatibility between the different "versions" of CDEPTH running on VMS, Unix and MS-DOS. The preprocessor PRECD has also been developed further, and version 1.3 of the code was released in September.

TABLE 3
NUMBER OF CDEPTH INSTALLATIONS AT VARIOUS SITES

LOCATION	*PC*	*UNIX*	*VAX/VMS*
OH/RD	2	3	2
OH/CPS	1		
OH/NED	1		1
AECL/CO	1		
AECL/CRL	1		
NBEPC/Pt. Lepreau	1		
HQ/Gentilly	1		

3.4.2 ***Evaluating CDEPTH Contact Assumptions***
(G. Morandin, N. Badie and R. Sauve)

In this study, a 3-dimensional contact algorithm (3DCA) which was developed in the Applied Mechanics Section was used to test the validity of the assumptions made in the CDEPTH contact algorithm, in particular, the value of the contact stiffness. Since at the moment the 3DCA can only be used in static loading cases, different lengths of contact were obtained by applying various loads to the models.

The contact algorithm used in CDEPTH was found to overestimate the contact length relative to the 3DCA in all cases when the currently accepted value of contact stiffness was used. As expected, refining the mesh with the same stiffness reduced the contact length predicted by CDEPTH. By changing the mesh size and contact stiffness over a range of values (mesh size: 2.5-15 cm, stiffness 1-10 MN/m) CDEPTH predictions were made to agree with the 3DCA. Then, different mesh sizes could be used to obtain the same contact length by scaling the contact stiffness with the mesh size.

When using the current value of contact stiffness (1.09 MN/m for Pickering-A, 0.82 MN/m for Bruce-A), CDEPTH predictions are in reasonable agreement with 3DCA predictions for contact lengths greater than 1 m. On the other hand, CDEPTH predictions for contact lengths of less than 0.5 m are much higher than 3DCA predictions. This has implications in terms of design equations: in contact studies to date, it has been noted that both sets of design equations, when used in CDEPTH, overpredict very short contacts. This work indicates that by revising the CDEPTH contact algorithm to modify the contact stiffness as the contact spreads, better agreement can be obtained between predictions and measurements of short contacts.

3.4.3 ***Analysis of Contact Data***
(N. Badie, R.A. Holt)

The contact database now contains 28 cases in P3 (6 cases), P4 (8), B1 (1), B2 (12), and L1 (1). Nine of these are PIE measurements, and 5 cases have been measured both with CIGAR and during PIE. The predictions of CDEPTH with both sets of design equations (CRNL-1993/1956 and CRNL-4000/4001) have been compared with these measurements. Since the predictions are sensitive to input data, two sets of inputs were used to obtain predictions.

Table 4 shows the results with one set of inputs: on average, CRNL-4000/4001 overpredict and CRNL-1993/1956 underpredict the length of contact. Also, both sets of design equations have comparable predictive capabilities, as shown by both the absolute and sum-of-squares measures of the errors.

TABLE 4

CONTACT PREDICTIONS VS MEASUREMENTS OF CONTACT LENGTH

	MEASURED (m)	*CRNL-1993/1956 (m)*	*CRNL-4000/4001 (m)*
Average	0.864	0.788	0.923
$\overline{P-O}$	-	-0.076	+0.059
$\overline{\lvert P-O \rvert}$	-	0.155	0.146
$\overline{(P-O)^2}$	-	0.035	0.032

Note: O: Observed, P: Predicted

3.4.4 *Modification of CDEPTH for On-Line SLAR Applications*
(N. Badie and R. Sauve)

The objective of this cooperative effort with Applied Mechanics Section is to make modifications and additions to CDEPTH and its pre-processor PRECD, such that the resulting code will be able to determine the optimal locations of spacers once their initial locations are known. This code could then be used to assist the SLAR team, and help reduce the down time of the reactor by a significant amount.

3.4.5 *Contact Data for Gentilly-2*
(N. Badie, D. Leemans and K. Linfield)

In order for a probabilistic assessment of blister formation to be carried out for the Gentilly-2 reactor, information on the initiation and spreading of contact in that reactor was required. Available data applied only to 2-spacer channels. To meet this requirement, it was decided to use CDEPTH to simulate the development of contact in a large number of channels with Gentilly-2 operating conditions.

Modifications made to CDEPTH and PRECD allowed a total of 366 simulations to be carried out. The CDEPTH output was post-processed to provide the contact data in tabular form to be used by the probabilistic assessment program REACTOR.

Some interesting patterns can be noted when looking at the results of this work:

(a) Because of the reduced diameter of spacer coils in G2, contact in a given span with similar operating conditions occurs earlier than in PNGS-A or BNGS-A channels. Also, the spreading of the contact is much more asymmetrical than in channels with thicker spacers.

(b) In modelling 30-year operation of the reactor based on CRNL-4000/4001, several channels with large spacer displacements were predicted to have two or even three distinct areas of contact along the channel length.

3.4.6 *Studies Related to Pickering-4 Shutdown*
(N. Badie)

Three channels which were predicted to be in contact by CRNL-4000/4001 and not by CRNL-1993/1956 were inspected with CIGAR, and no contact indications were found. All three of the channels had small inboard displacements of their outlet spacers (12-16 cm). Apart from its operational implications (i.e. that channels with smaller inboard movements of their outlet spacers need not be examined for contact) this finding may have implications for the design equations.

Related to this subject is the PIE inspection of some removed tubes from Pickering Unit 3. These tubes had inboard displacements of their outlet spacers by approximately 30 cm, and had white marks characteristic of contact on their outlet sections. CDEPTH calculations show that according to CRNL-4000/4001, the contacts are predicted to have occurred 2-3 years before shutdown, whereas according to CRNL-1993/1956, contact was not predicted.

3.5 *Fuel Channel Deformation Database*
(S. Perkons)

A dBase IV menu-driven application has been written for accessing, displaying and manipulating fuel channel deformation data. The intent is to make the database available to COG members in a run-time or executable version, enabling users to have access to the data without having to purchase dBase IV.

The database itself consists of operating and inspection data. Individual files exist for sag and diameter gaugings for individual fuel channels. Operating conditions files exist for individual reactors. See Table 5 for a list of the currently available data.

The diameter database files include forward and reverse minimum, maximum and mean diameters as well as ovality, at 50-80 points along the channel. The sag files contain measured and calculated deflection, curvature and slope at 40-50 points along the channel. Operating conditions files contain time averaged temperatures at the downstream end of each fuel bundle and fluence at mid-bundle locations for every channel in a given reactor.

4.0 *DEVELOPMENT AND APPLICATION OF SPECIALIZED TECHNIQUES FOR MECHANICAL AND PHYSICAL PROPERTY MEASUREMENT*

4.1 *Development of Techniques for the Nondestructive Evaluation of Hydrogen in Zirconium Pressure Tube Material*
(K. Tashiro and D. Oad)

4.1.1 *Calorimetric Measurements*

The accelerated development of calorimetry was initiated in order to provide an alternative method of determining the hydrogen equivalent concentration of the P4 and B1 scrapes.

The calorimetry cell was remotely located in a hot cell and tested on several high fluence irradiated wafers taken from pellets. A concentration was calculated using the average of various TSS equations given the temperature from calorimetry. The agreement is generally favourable. However, the difference in concentrations can be either random or linearly dependent depending on which chemical analysis method the calorimetric results are compared to.

TABLE 5

AVAILABLE DATA IN FUEL CHANNEL DEFORMATION DATABASE

DATABASE	*UNIT*	*CHANNELS*	*DATE*	*EFPH*
Operating Conditions	B1	all	04/90	83500
	B2	all	12/86	61300
	B3	all	12/90	85600
	P3	all	05/89	117300
	P4	all	04/90	119000
Diametral expansion	B1	L08,N03,R03	05/83	39600
	B2	K07,L08,013,T12	03/74	0
		K07,L08,013,T12	01/83	35800
	P3	K05,J17,M11,M12	11/71	0
		K05,M11	07/73	6800
		J17,M12	05/74	13000
		K05	05/78	38500
		K05,J17,M11,M12	10/79	48600
		K05,J17,M11,M12	10/82	72500
		J09	04/84	83700
Sag	B1	L08,N03,R03,S13	11/74	0
		L08,N03,R03,S13	05/83	39600
	B2	K07,L08,013,T12	03/74	0
		K07,L08,013,T12	01/83	35800
		K03,K07,L08,013, P12,R07,R12,S09, S10,S13,S22,T08, T12,T15,T18,T19, T20,U07,U13,V17	09/85	54800
	B3	L08,S13	12/76	0
		L08,S13	11/84	47900
	B4	013,R03	01/78	0
		013,R03	04/85	43900
	P3	J17,K05,M11,M12	11/71	0
		K05,M11	07/73	6800
		J17,M12	05/74	13000
		J17,M05,M11,M12	10/79	48600
		J17,K05,M11,M12	10/82	72500
		M12	07/87	104500
	P4	J17,K10,L08,L10, L13,M11,M12,Q12, U12	03/86	92500
		F09,L21,011,P09, P15,U16,W11	02/89	111900

The actual scrapes are received as a tight curl and it was necessary to have them flattened and then spot welded to hold them flat. It was observed that P4 scrapes were stiffer than their B1 counterparts.

A limited number of calorimetric measurements have been performed on the accompanying oxide covered scrapes from the P4 scrape campaign. It has been found that the oxide covered scrapes agree with their oxide free counterparts when the overall concentration is high. If the overall concentration is low, the oxide covered scrape tends to predict a higher concentration.

Generally, oxide covered scrapes produce considerably higher deuterium concentrations when analysed by vacuum extraction. An oxide covered scrape was halved, one half being subjected to calorimetric measurement then both pieces submitted for vacuum extraction analysis. The analysis of the calorimetric portion yielded deuterium levels in near agreement with those calculated from calorimetry. The other portion returned extremely high deuterium levels. It is believed that the extra deuterium in the oxide can be desorbed from the scrape by the thermal treatment that calorimetry introduces. This thermal treatment of oxide covered scrapes may allow for meaningful analysis of these scrapes.

Comparison of the hydrogen equivalent concentrations obtained from calorimetry and extraction analysis have been favourable. Discrepancies still appear when the scrape has oxide remaining on it. Since calorimetry can only yield a hydrogen equivalent concentration, the hydrogen concentrations are required for the scrapes. Hydrogen concentrations yielded from scrape analysis were believed to be far too scattered and too high in some instances to be realistic. Therefore, the total hydrogen equivalent concentrations were derived using deuterium concentrations derived from the scrapes and the hydrogen concentrations were derived from pellet analysis of the offcuts.

Figure 4 illustrates the agreement between calorimetric analysis and vacuum extraction analysis for NGS P4. Further studies of these two techniques are planned.

During preliminary scrape measurements, an anomalous deuterium pickup effect was observed when scrapes are abraded in heavy water. This observation has led to the development of a technique to measure small concentration differences between scrapes.

Vacuum extraction analysis of pellets taken from P4C17 and P4C18 at the scrape location shows a considerable decrease in deuterium levels when compared to the scrape analysis. In order to confirm this decreased deuterium level, sections of pellets from the same area were measured by calorimetry. The pellet temperature was considerably lower than the scrape temperature. This temperature decrease was converted to a equivalent hydrogen concentration decrease, which agreed with the results of vacuum extraction analysis. It can be concluded that the scrape was contaminated.

4.2 *Materials Properties and Biaxial Deformation Behaviour for CANDU Reactor Zircaloy-4 Fuel Cladding at Elevated Temperatures in Air and Steam Environments (COG WP2887)*

(E.T.C. Ho and A. Donner)

4.2.1 *Biaxial Deformation Behaviour in Flowing Steam Environments*

When a fuel cladding sample is subjected to a sufficiently large differential internal pressure at elevated temperatures, the tube will deform by expanding outwardly or ballooning. However, the exact nature of the deformation will be determined by such factors as:

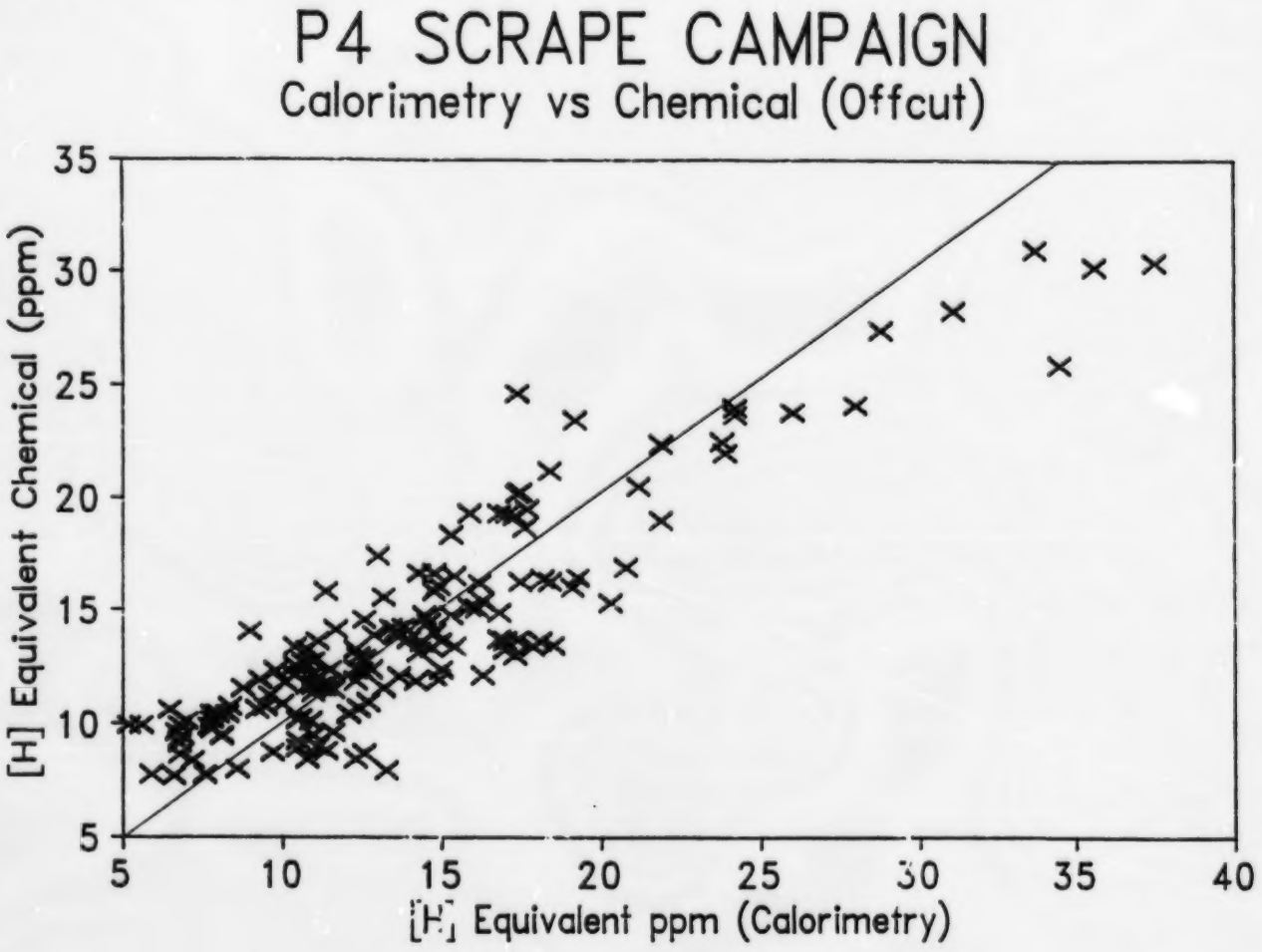


Figure 4 Comparison of equivalent hydrogen concentration derived from calorimetric measurements and vacuum extraction analysis for the NGS P4 scrape campaign. The vacuum extraction analysis values were derived using the deuterium concentration from the scrapes and the hydrogen concentration from the offcut pellet analysis.

1. the relative magnitude of the differential internal pressure;
2. the magnitude of the elevated temperature;
3. the time at temperature;
4. the tube sample external environment.

For a given set of conditions, one or more of the above factors may be dominant or rate controlling.

Data obtained from the biaxial tests carried out in steam indicate that the mechanisms described previously for the biaxial deformation behaviour in air are complicated by the nature and kinetics of hydrogen ingress into the metal substrate. Based on information obtained to date, it appears that the additional factors governing the biaxial deformation behaviour in steam are:

1. the effect(s) of hydrogen in solid solution in α-Zr on high temperature deformation behaviour;
2. the kinetics and nature of the α→ß phase transformation due to hydrogen uptake by the substrate α-Zr phase;
3. the deformation behaviour of duplex α+ß (hydrogen-stabilized ß) microstructures in parent material at elevated temperatures;
4. the behaviour of duplex prior transformed ß (due to brazing cycle) and hydrogen-stabilized ß microstructures in braze HAZ material at elevated temperatures;
5. the deformation behaviour of the parent/braze HAZ transition region.

4.2.2 ***Hydrogen Ingress or Uptake Behaviour During Elevated Temperature Exposure in Flowing Steam Environments***
(E.T.C. Ho and A. Donner)

Early results obtained from oxidation and biaxial deformation tests in flowing steam indicated that both the oxidation kinetics and the biaxial deformation behaviour were significantly different from those observed in air. Subsequent metallography and mechanical testing showed that the above difference in behaviour may be attributed to the absorption or uptake of hydrogen by the Zr metal substrate. In view of this, a test program was undertaken to investigate the nature of hydrogen ingress in Zr-4 fuel cladding samples during exposure to flowing steam at elevated temperatures.

Weight gain and outer diameter (OD) oxide thickness results obtained for hold times of six (6) hours at temperatures in the range 650-850°C are presented in Figures 5 and 6, respectively. The data obtained to date may be summarized as follows:

1. the oxidation kinetics exhibit a maximum plateau over the temperature range 740-760°C and sharp drop over the temperature range 760-775°C;
2. the minimum in oxidation kinetics occurs at about 775°C;
3. the results showed clearly that high hydrogen ingress is associated with the attainment of post-transition (ie linear) oxidation kinetics;
4. the data also indicate that the oxygen-stabilized α-Zr layer may play an important role in the overall hydrogen ingress mechanism;
5. the oxidation kinetic data obtained agree very well with the data reported by Leistikow et al at 650, 700 and 850°C, but differ dramatically at 800°C and substantially at 750°C.

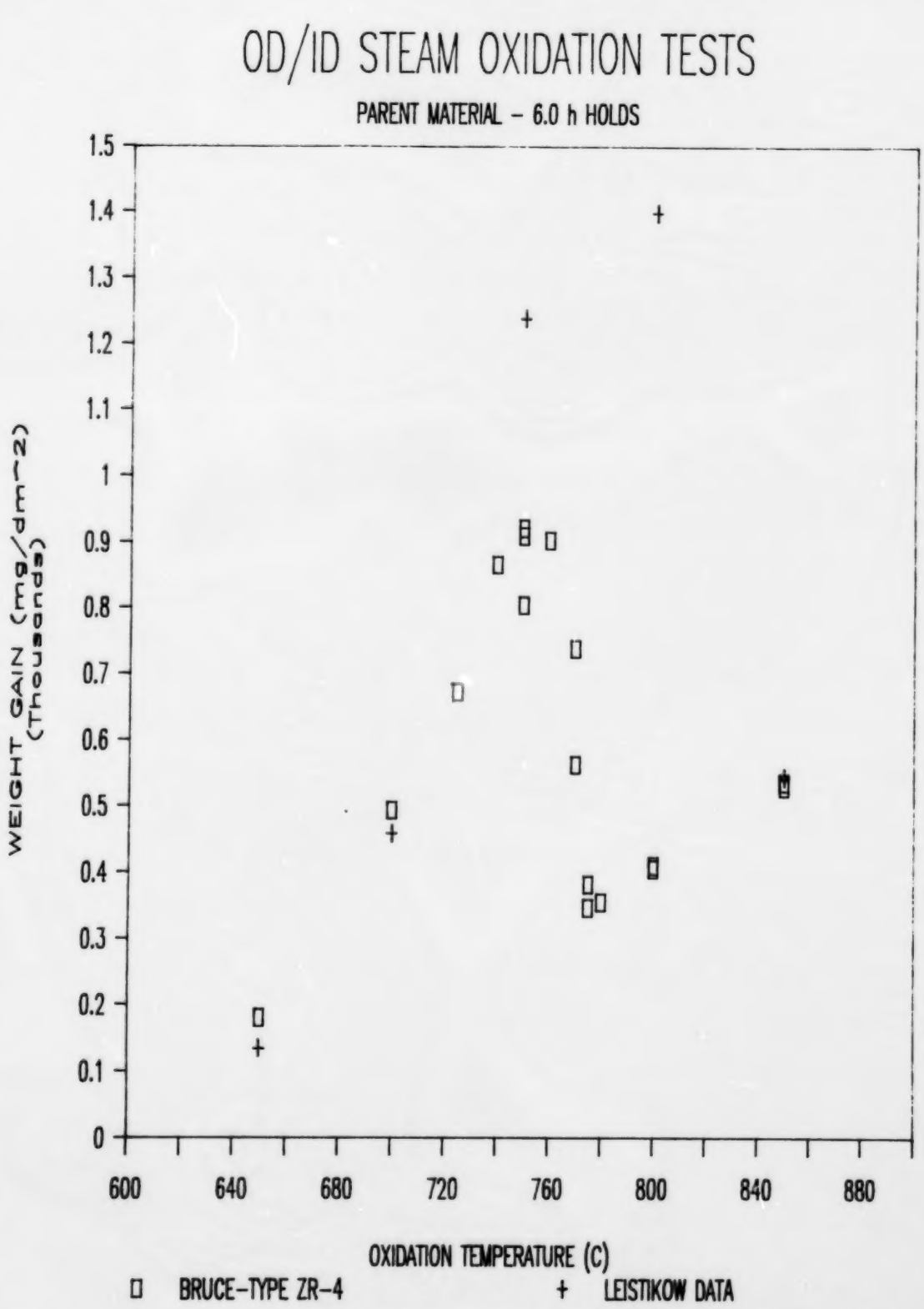


Figure 5 Plots illustrating variation of weight gain in parent Bruce-size Zircaloy-4 fuel cladding material as a function of steam oxidation temperature for 6.0 h isothermal exposures.

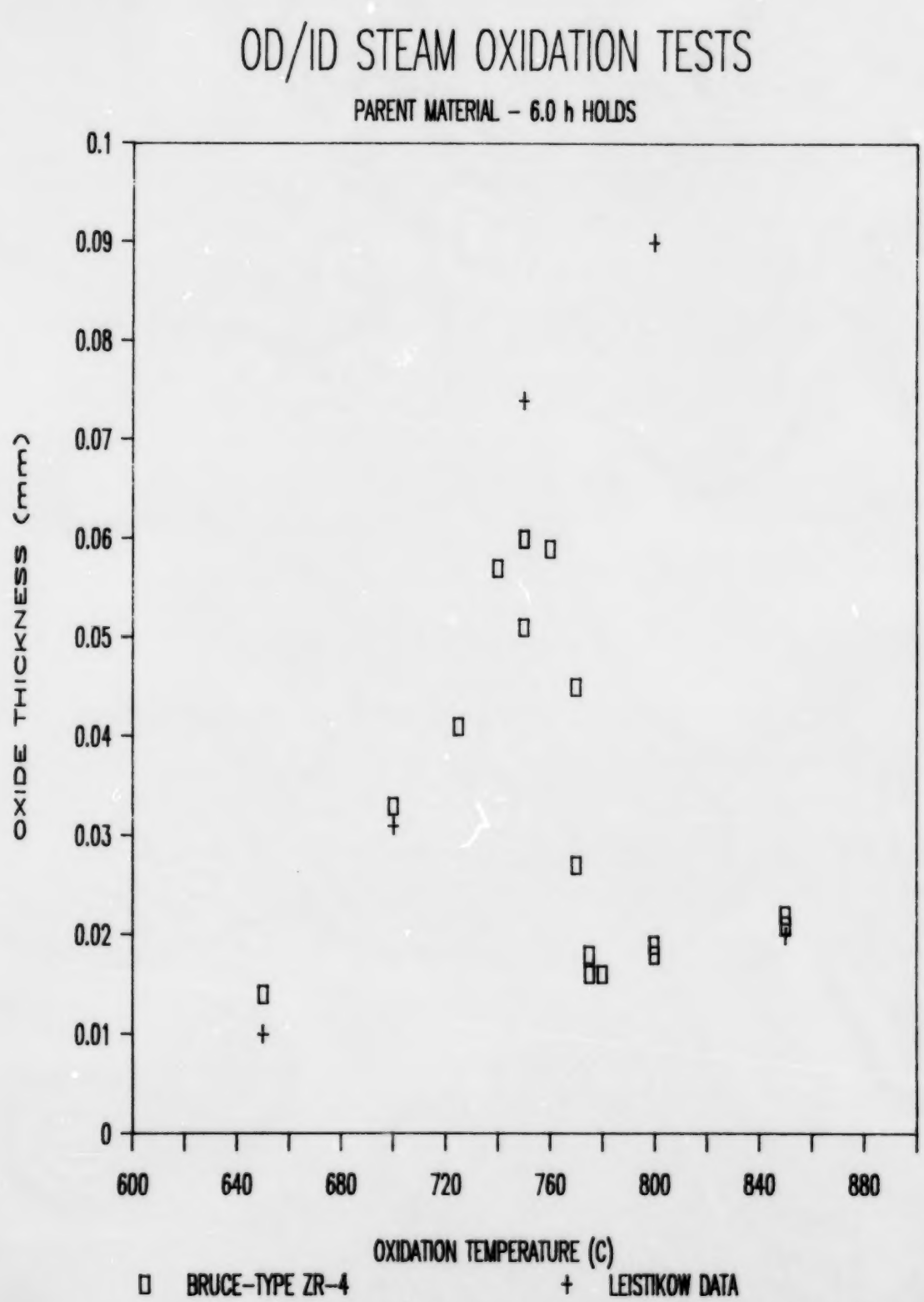


Figure 6 Plots illustrating variation of OD oxide thickness in parent Bruce-size Zircaloy-4 fuel cladding material as a function of steam oxidation temperature for 6.0 h isothermal exposures.

4.3 *Special Studies*

4.3.1 *Method to Produce ID-initiated Cracks in Zr-2.5 Wt% Nb Pressure Tube Specimens*

(E.T.C. Ho and M.J. McGraw)

A test fixture and an experimental procedure have been developed whereby axial, ID-initiated cracks can be produced in lengths of Zr-2.5 Nb pressure tube material without the use of a machined starter notch. The procedure developed is based on cyclic compression or squeezing of a length of Zr-2.5 Nb pressure tube specimen which is held in a custom-designed test fixture. Results obtained indicate that an ID-initiated crack of any desired depth in the range 0.25-3.5 mm can be produced. However, the results also showed that the crack initiation or nucleation event is very sensitive to the condition of the tube ID surface in the immediate vicinity of maximum stress concentration. In some cases, cracks have been observed to nucleate at deep honing marks and deliberate shallow axial scratches on the ID surface of the tube specimens.

4.3.2 *Compression Testing of Zr-2.5 Wt% Nb Pressure Tube Materials*

A loading fixture suitable for carrying out compression tests under approximately constant applied strain rate conditions has been designed, built and tested out. Computer application programs for test control, data acquisition and data analysis for compression testing have been developed and tested out. To date, a limited number of compression tests have been carried out using mainly TG3-R1 Zr-2.5 Nb PT materials. A summary of the compression test results obtained is presented in Table 6.

TABLE 6

SUMMARY OF COMPRESSION TEST RESULTS

MATERIAL	*TEMP (°C)*	*STRAIN RATE (s^{-1})*	*0.2% YS (MPa)*	*FRACTURE STRAIN*
Swaged Rod	20	$1x10^{-3}$	498	--
"	"	"	512	--
TG110B	"	"	613	--
"	"	"	635	--
TG097B	"	"	545	--
"	"	"	553	--
TG075B	"	"	619	-0.427
"	"	"	616	-0.401
"	"	"	604	-0.415

Results obtained from the compression tests carried out to date show clearly that the compression stress-strain curves are affected strongly by the texture and cold work level of the starting PT material. It appears that the state of the starting material may be deduced from a detailed examination of the compression stress-strain curve for the material.

4.3.3 *Stress Relaxation Testing of Zr-2.5 Wt% Nb Pressure Tube Materials Under Strain Control Mode*

An experimental procedure and necessary computer software have been developed to carry out stress relaxation testing.

Figure 7 is an example of stress relaxation data from tests carried out using standard Zr-2.5 Nb PT material at 250°C. The data shows clearly that the initial relaxation or rate of stress decrease is very rapid. However, the remainder of the stress relaxation curve consists of a long duration, continuously decreasing rate of stress relaxation. The data also shows that the peak stress attained was well above the proportional limit for the material.

5.0 *PRESSURE TUBE FABRICATION*

5.1 *Modified Pressure Tubes*
(E.T.C. Ho and M.J. McGraw)

5.1.1 *Tensile Properties*

Results obtained from tensile testing of some 1988 as cold-worked TG3-R1 material after various draws or cold work levels (in a four-draw schedule) indicate that both the 0.2% offset yield strength and the tensile strength increase with increasing cold work, as shown in Figure 8. After about 40% cold work (i.e. overall reduction of area), the PT material still appears to retain sufficient ductility to meet the minimum % elongation specification (12%) for the current pressure tubes. The data also indicate that the bulk tensile properties of the 1988 TG3-R1 pressure tubes are not significantly different from those of the original TG3-R1 pressure tubes or the current standard pressure tubes. Therefore, it appears that the fabrication difficulties experienced with the two batches of 1988 TG3-R1 pressure tubes can not be delineated by conventional tensile tests.

5.1.2 *Microhardness Properties*
(with summer student J.F. Pringle)

By carrying out hardness measurements in the three principal directions of the pressure tube, the anisotropy in strength of the pressure tube material can be assessed.

For this investigation, sixteen (16) different Zr-2.5 Nb pressure tube materials were examined. Five of these materials were in the as-extruded state. The other eleven consisted of materials (mostly TG3-R1 pressure tubes) in various cold worked stages ranging from one to four draw passes. Results obtained indicate that the KHN data allow a relatively detailed assessment of the anisotropy in strength of the Zr-2.5 Nb PT materials. The KHN data also showed that for some of the materials examined, the KHN just below the ID and OD surfaces was slightly larger than that of the bulk material. However, this difference, where it existed, was generally quite small (2-10 %). Comparison of the anisotropy in strength deduced from the KHN data with that obtainable from measurement of the texture indicates that the two results are consistent and in relatively good agreement.

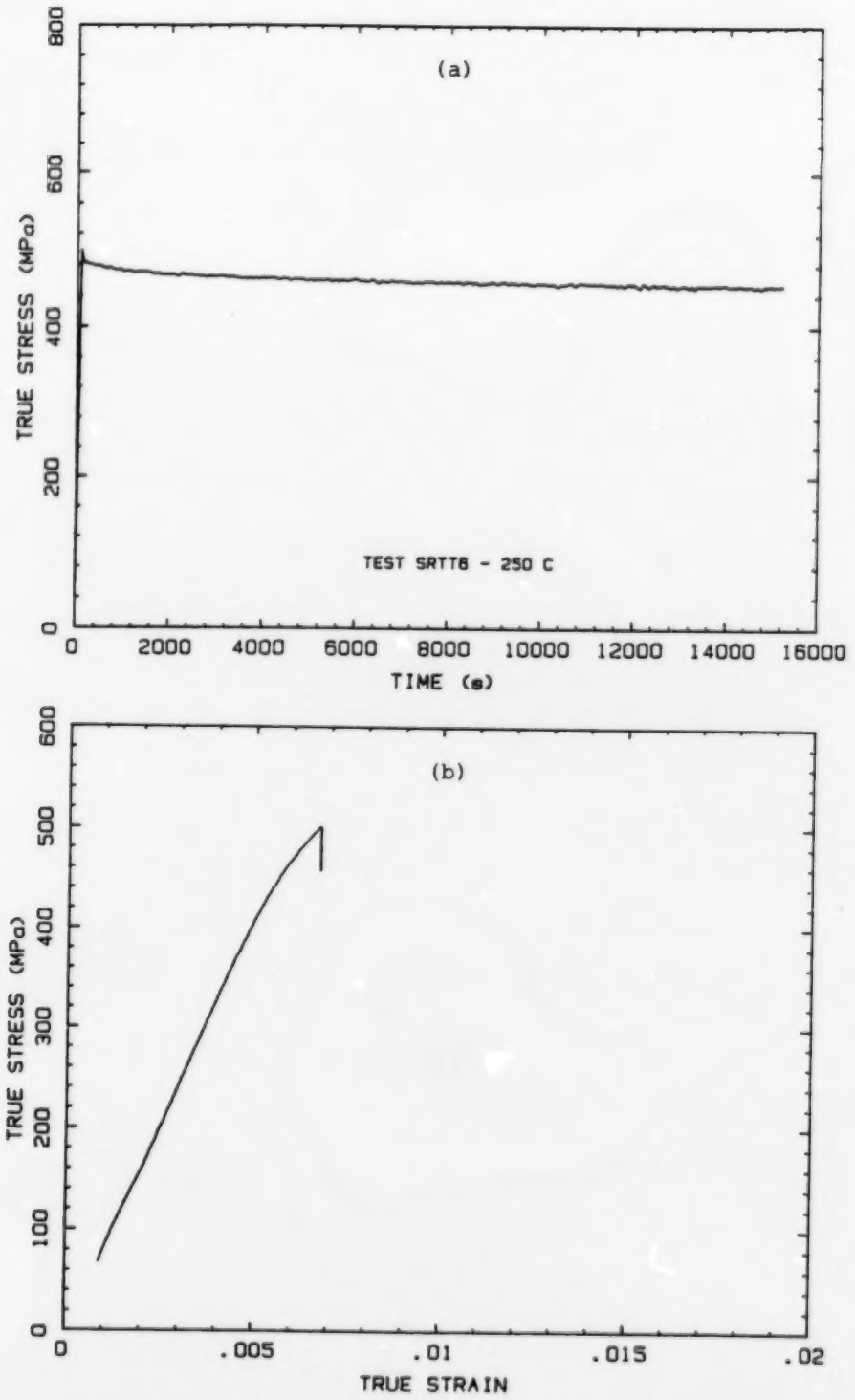


Figure 7 Plots illustrating experimental data for standard Zr-2.5 Nb PT material obtained in a stress relaxation test carried out at 250 C: (a) true stress vs time data; (b) true stress vs true strain data showing effectiveness of strain control and degree of stress relaxation.

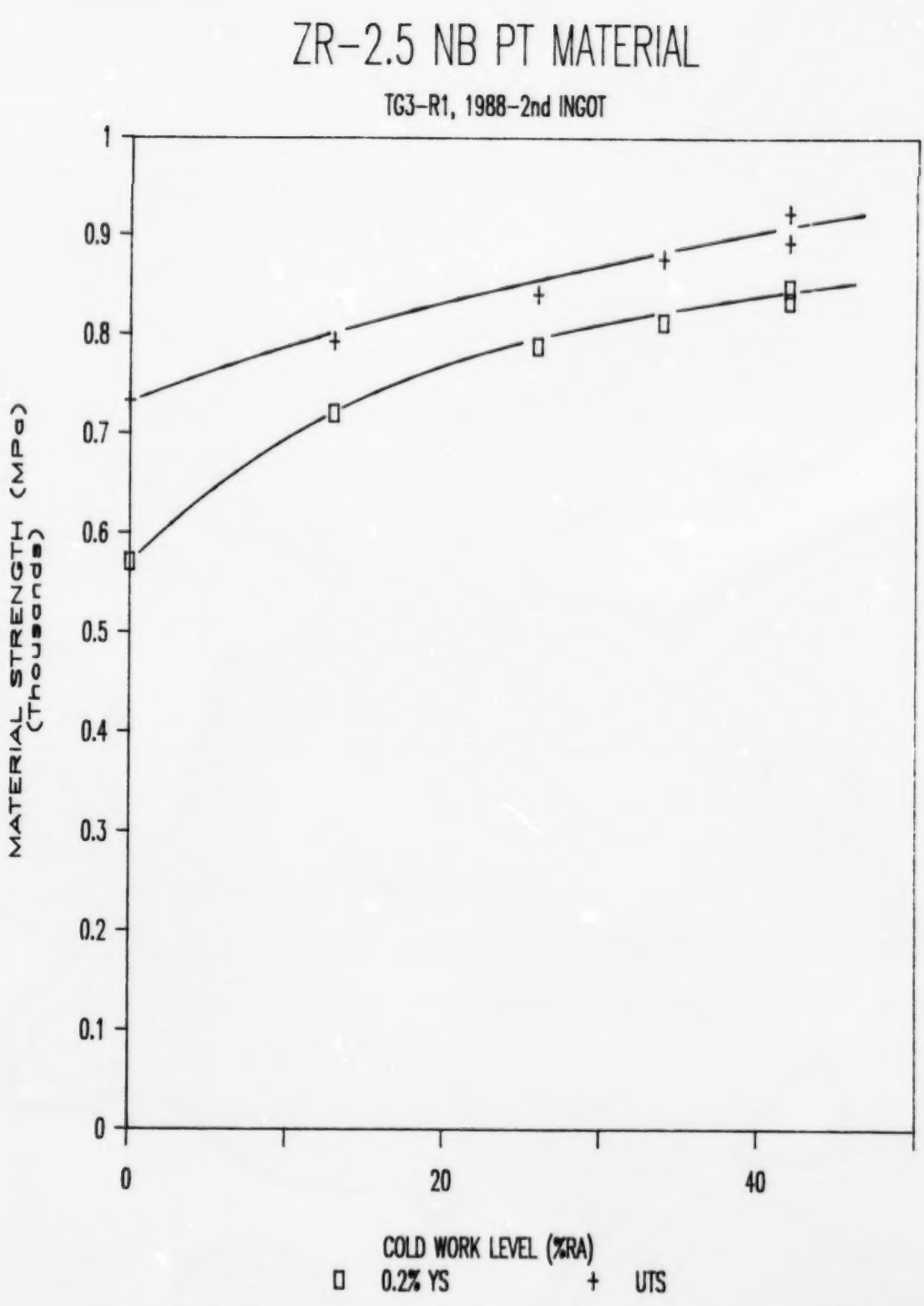


Figure 8 Plots illustrating variation of 0.2% offset yield strength and ultimate tensile strength with cold work in some 1988 TG3-R1 pressure tube materials after various draw stages.

5.1.3 *Metallurgical Investigation of Transverse Defect Indications in PT TG075*

Three of the TG3-R1 pressure tubes fabricated in 1987 and 1988 (TG019, TG075 and TG078) showed ID surface transverse defect indications during final UT inspection of the tubes. Subsequent metallurgical investigation of three (3) of the five (5) transverse defect indications in tube TG075 found that the defect indications were transverse shear cracks. These shear cracks were similar to the shear cracks observed previously in some of the two batches of 1988 TG3-R1 tubes, in the as cold worked condition. The metallurgical investigation of these defect indications is continuing.

5.1.4 *Cold Drawing of Pressure Tube Extrusions*

A possible solution (suggested by Professor B. Avitzur, a metal forming consultant) to the shear cracking problem encountered with the two batches of 1988 TG3-R1 tubes proved unworkable with the existing draw bench equipment at Nu-Tech. Although three (3) 1988 pressure tube extrusions (second ingot) were processed with no apparent problems using a small (2°) semi-cone angle die of the current Nu-Tech draw die design, in the first draw of a three-draw schedule, subsequent attempts to perform the second draw using 2° and 6° semi-cone angle dies resulted in fracture of the dies during initial loading of the tubes. Without major modifications to the current die setup, it appeared that the only alternative was to investigate the use of a composite die whereby the inner rings of the die can be placed in compression to extend the range of usable hoop stresses.

In view of the above, Advanced Wire Die of London, Ontario was consulted. They proposed a three-layer composite die design (second draw, 6° semi-cone angle) which can be accommodated with the current die setup at Nu-Tech. The above die was fabricated and subsequently used to draw successfully the three tubes processed previously using a low angle standard die. It now remains to determine the appropriate die bore dimensions for a third draw composite die, since the spring back associated with the composite die was greater than that observed with the standard dies.

A contract has been set up with Nu-Tech to fabricate thirty-five (35), 1/5-scale Zr-2.5 Nb pressure tube extrusions. These scaled-down extrusions will be used to carry out cold draw experiments to investigate more quantitatively the effects of process parameters on tube quality and formability during the cold draw stage of tube fabrication.

5.1.5 *Contract with the University of Toronto*

A research contract funded by the Materials Technology Section was awarded to the Department of Metallurgy & Materials Science of the University of Toronto. The main objective was to increase the very limited number of researchers conversant with the deformation and metal working characteristics of Zr-2.5 Nb PT materials.

6.0 *ADVANCED INDUSTRIAL MATERIALS*

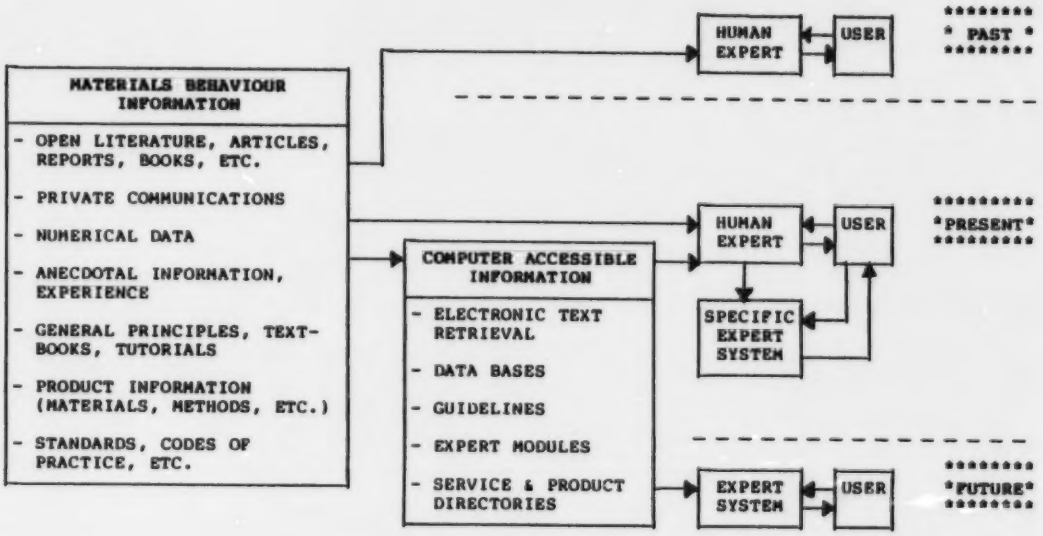
6.1 *Expert Systems to Diagnose Material Problems*
(P. Mayer)

Millions of dollars can be saved by better utilization of the available information on materials properties and performance. One of the obstacles in realizing these savings is the difficult access to this expertise. At present, it is inconvenient, tedious and time consuming, even for an experienced specialist. This makes, frequently, the application of expertise to solve a

materials performance problem too expensive, when compared with a simple expedient of replacing a failed component with the same one. While this may seem satisfactory in a short run, recurrence of the same problem is virtually guaranteed in the future.

Recent developments in the information technology (both hardware and software) hold a promise to overcome the problem of information accessibility.

It is possible that the process of expertise application will change in the future according to the following model:



The key to the successful implementation of the computer accessible process of expertise application, is development of expert systems.

At present, development of seven expert systems, addressing materials performance problems in fossil fired stations was completed. These are available for use by Ontario Hydro.

6.2 ***Director's Fund Project - High Temperature Superconductor/Metallic Conductor Contacts for High Current Application in Power Systems***
(A.V. Manolescu, P. Mayer, S. Krishnasamy, E. DiBlasio, M. Eygenraam)

Use of high temperature superconductors (HTSC) in the electric power system depends on the development of HTSC conductors with reliable connection to metallic conductors. The HTSC/metal contacts must join mechanically together two fundamentally different materials, and be able to carry high currents with minimal resistance loss to avoid local heating that may lead to loss of superconductive properties.

Research work has been carried out to identify and develop a technique to join HTSC with metallic conductors for high current applications in the power system. Silver was identified as a contact material because of its low affinity to oxygen, and good mechanical and electrical properties. Soldering was selected to join the metallized HTSC material, with the metallic conductor, copper or silver wire.

Laboratory tests designed to characterize the metallized samples showed that silver contacts deposited from a Ag-expoxy slurry using an "in-house" developed technique exhibited best performance characteristics. Metallographic analysis indicate that the deposited silver contacts have an excellent adherence to the ceramic substance and a very low resistivity. Surface analysis of the samples indicated that the contacts are stable under both ambient and cryogenic conditions.

A final contact interface configuration has been designed, fabricated, tested and proven capable to carry 100 A of continuous dc without a loss of superconducting properties.

The program is now completed and opportunities for commercializing the material fabrication and contact metallization are being examined. A patent application is being prepared.

6.3 ***Advanced Materials Use in Transmission and Distribution Lines***
(P. Mayer, G. Bellamy)

A general solution to this fundamental problem of line outages is to use materials possessing superior properties and/or superior finished quality. This was not always possible in the past, since the materials often did not exist and in some cases where superior materials were available, their cost made use prohibitively expensive.

These barriers can be overcome today for some applications through the use of currently available advanced materials, which are primarily composites of metal ceramics and polymers. As a result high performance materials are available today with significantly improved mechanical and environmental stability.

Consequently, an opportunity exists to improve the reliability and performance of transmission system equipment by selective application of advanced materials. Since this is a complex task, it will require a focused, multidisciplinary effort to combine the developments in material technology with system requirements.

A key step in this process is to identify superior materials which are available today and determine where their use will minimize or resolve existing problems.

Multi-disciplinary research efforts isolated the life limiting factors affecting overhead transmission systems. The key issue is corrosion of galvanized steel core wiring in A.C.S.R. conductors. Destructive environmental components were identified. Their distribution and concentrations were plotted across the Province by the Environmental Research Department and life predictions were prepared for areas of interest. The Mechanical and Electrical Research Departments were also involved in testing and condition monitoring roles respectively.

6.4 ***Metal Matrix Composite for Overhead Line Components***
(P. Mayer)

Al-SiC materials containing up to 20 vol % of the reinforcing ceramic exhibit significantly higher yield strength, modulus of elasticity and ultimate tensile strength than the parent alloy. In order to exploit these properties to enhance the performance of power line hardware made of aluminum, the composite materials must be optimized to increase their ductility (% elongation and UTS). This can be achieved through addition of minor alloying elements, heat treatments, etc.

A program of property optimization consists of two phases:

1. Verification of properties of commercially available composite materials using test methods required by Ontario Hydro specifications.

2. Optimization of properties of commercially available materials if necessary to exceed current Ontario Hydro specifications by:

   - Modifying metallurgy of the composites by addition of modifiers,
   - Improving properties by suitable heat treatments.

The first phase is in progress; tests of mechanical properties and environmental behaviour of this material are underway.

The second phase, which will be carried out in cooperation with CANMET and Brampton Foundaries Inc. will be initiated in the first quarter of 1991. Work at Ontario Hydro will focus on the mechanical testing and materials characterization segments of the joint program.

6.5 ***Transmission Systems***
(P. Mayer, G. Bellamy)

A joint CEA study between Ontario Hydro and Hydro Quebec was initiated to identify opportunities with potential to improve transmission line performance, reliability and safety through implementation of advanced materials.

In the first phase of the study, a review of transmission line problems, is in progress. The objective is to identify those caused by material failures. In the second phase, advanced materials will be selected and their potential to resolve these problems will be assessed.

6.6 ***High Temperature Erosion/Corrosion Coatings for Fossil Fired Stations***
(J.O. Noga)

A joint program was initiated between Ontario Hydro and CANMET to evaluate the use of ductile nickel aluminide coatings to reduce erosion/corrosion in susceptible components operated by Ontario Hydro. The aluminide being tested is aluminum lean (ie, Al < 25 atomic percent) Ni_3Al with boron additions (approximately 200 ppm) which results in a ductile, oxidation resistant material.

Additional properties which this material exhibits are good high temperature creep properties and an increasing yield strength with temperature to 850°C. The immediate application, if warranted by test results, will be to protect boiler tubes in areas where tube wastage is excessive and cannot be stopped by deflection plates. Other potential applications include both steam and gas turbines where erosion, oxidation and corrosion are life limiting degradation mechanisms.

During 1990 Ni_3Al material was produced in powder form suitable for both flame and plasma spraying. Work has started to establish process parameters to spray Ni_3Al using a high velocity flame spray technique (Jet Kote).

6.7 *Rapidly Solidified Metal Properties and Applications*
(J.O. Noga)

Rapid solidification processing (RSP) is becoming a more important technique to produce new alloys and improve properties. A great deal of effort is currently underway by industry to increase the strength and other mechanical properties of aluminum alloys at ambient and high temperatures through rapid solidification techniques. A commercially available RSP aluminum alloy containing 1% zirconium was examined using TEM and SEM techniques. This material exhibited an average grain size of about 1.5 μm and extensive dispersoids approximately 7.6 nm in diameter. There was significant interaction between the dispersoids and dislocations which accounts for the high tensile strength exhibited by the alloy.

6.8 *Evaluation of Coatings Technology*
(J.O. Noga, G. Bellamy)

There are numerous potential applications for coatings in current and proposed Ontario Hydro operations. A review was conducted of coating methods and properties covering all potential uses. A review of combustion turbines noted numerous performance problems related to turbine coating/superalloy substrate combinations which must be resolved in order for acceptable operation to be obtained from this technology.

The possible introduction of large, base loaded gas turbine powered generators into the Hydro system prompted research into relevant materials selection, performance and rehabilitation.

6.9 *Lead Alloys*
(G. Bellamy)

Research activities were pursued in a number of areas. Studies on the metallurgy of lead and its alloys continued in a search for maintenance-free standby power cells for nuclear control systems. A broadening of this activity was undertaken in an effort to understand the requirements for and service behaviour of lead alloy sheathing on high voltage underground conductors.

6.10 *Aluminum Castings*
(G. Bellamy)

A CEA funded program on the fracture properties of advanced aluminum alloy castings is proceeding on schedule and within budget. Test castings were produced under stringently controlled conditions in three alloys of interest to Transmission Design. Optimal microstructures were produced by appropriate control of alloy solidification rates and heat treatment parameters. Environmental concerns have outlawed the use of chlorine for alloy degassing and some problems were encountered with substitute systems. Work is in progress to resolve these.

7.0 *FAILURE ANALYSIS*

(G. Bellamy)

During 1990 forty-one failure analysis reports were issued. Synopses of the most noteworthy will follow.

As the year began disturbing reports emanating from Darlington NGS indicated an unacceptable tendency for the structural steel supporting nuclear control cables to fail by brittle fracture under the influence of very light shock loading. Susceptible components were cold formed from a variety of rimmed, semi-killed and fully silicon killed low carbon steels. Failure was caused by strain aging, hydrogen embrittlement and liquid metal embrittlement during hot dip galvanizing. These tendencies were exacerbated by use of a brake press to make very tight bends of uncontrolled radii. Remedial recommendations included specification of fully aluminum killed ASTM A620 or A622 steels together with a minimum cold forming radius of three times the material thickness.

Gross dilution from underlying carbon steel and use of an inappropriate welding consumable resulted in excessive carbon concentration in an austenitic stainless steel single pass, submerged arc overlay. This produced a sensitized microstructure during stress relief heat treatment and through deposit intergranular corrosion in critical components of a Darlington reactor's moderator system. A suggested repair procedure would utilize multi-pass shielded metal arc weld overlay deposits. The first pass would be in ENiCrFe-3 alloy to ASME specification SFA 5.11. Subsequent deposition would be in alloy E309L to ASME specification SFA 5.4.

Continuing cooperation with both the Mechanical Research Department and the Health and Safety Division culminated in recommendations for safe and efficient brake lining materials to replace hazardous asbestos based components in pumped storage hydraulic generating units.

Shortly after commissioning in 1974, a Nanticoke generator suffered catastrophic failure of an end ring. Design modifications essentially eliminated the likelihood of repetition. However, recent inspection revealed circumferential, generator rotor cracking associated with the bayonet fitting area where the end ring failure had initiated. The cracking mechanism was identified as low cycle fatigue. Responsible stress cycles appear to coincide with periodic removal and refitting of end rings. The cracks were machined out. Stress concentrating rotor lug radii in crack susceptible areas were removed by dispensing with the lugs.

Substantial design deficiencies in Lennox GS induced draught fans were revealed by metallurgical analysis. The very large welded carbon steel fabrications suffered multiple high cycle fatigue failures at points of excessive stress concentration. Premature bearing failure was also attributed to poor design and consequent excessive static stresses. Major design changes are in progress.

Repetitive, premature high cycle fatigue failure of thin walled, convoluted, flexible hydrogen hoses on nuclear station generators prompted a review of both design and material selection. The failures were in cold formed A.I.S.I. type 304 austenitic stainless steel fabrications. For convoluted hose, the much greater fatigue resistance of precipitation hardened type A286 stainless steel was recommended. Alternatively, abandonment of flexible hoses in favour of a rigid piping system would also solve the problem.

The master link failed on a PNGS fuelling machine elevator chain. Not only had the supplier randomly substituted two different materials in various critical components, but one of the materials (A.I.S.I. type 410 martensitic stainless steel) was supplied in the as-quenched condition with a very high susceptibility to the observed intergranular stress corrosion cracking mechanism. Ideally the failure prone chain side plates should have been fabricated in type XM13 precipitation hardening stainless steel and then heat treated to the H1100 condition.

Numerous problems have arisen with springs fabricated in cold reduced austenitic stainless steel strip. Reed elements in Darlington NGS annulus gas compressor valves and brush springs in hydraulic generators exhibited very poor serviceability in response to normal high cycle fatigue stresses. The ultra-clean, high strength, XM13 stainless steel mentioned above is particularly well suited for this type of service. It was recommended with a final heat-treatment to the H1000 condition.

During the year assistance was extended to two municipal utilities facing possible litigation. Our evidence persuaded the prosecuting counsel to drop charges against York Hydro in a case involving failure of safety devices on an ultra-lightweight ladder. In the second instance a key bearing failed on an Ottawa Hydro twin bucket man lift. Evidence arising from our investigation transferred blame from the utility to the equipment suppliers. High cycle fatigue failure clearly resulted from errors in assembly rather than poor maintenance.

8.0 *1991 PROGRAMS*

8.1 *Irradiation Damage and Deformation Studies*

8.1.1 *Microstructural Studies*

Work will be continued on TEM/AEM analysis of irradiated Zr-Nb alloys. One part of study will be related to the characterization of irradiation induced <a> and <c> defects. The research concerned with the <a> defects will involve more detailed stereo microscopy, post irradiation annealing and cleaning of thin foils. The aim of this study is a better understanding of the nature of <a> defects and the role of α-β interfaces and α-α sub-boundaries in fine grained Zr-Nb alloys as effective sinks for irradiation induced defects.

The study of the <c>-component defects is equally important. Further research will be focused on the origin of these dislocations and their possible connection with the intergranular constraints generated by irradiation growth.

The work on iron segregation will also continue and it will involve monitoring the iron presence and distribution in both unirradiated and irradiated Zr-Nb alloys subjected to various thermo-mechanical treatments.

A preliminary TEM study of irradiation damage generated in creep and growth specimens irradiated in the proton accelerator is planned. The results of these analysis will be used in a study of the mechanisms contributing to creep and growth in zirconium alloys. The study will be done in collaboration with AECL-CRNL and AECL-WNRE.

It is proposed to study the role of internal grain-interaction stresses on hydride precipitation in an Zr-2.5% Nb alloy. The residual stresses will be characterized by neutron diffraction techniques and hydride morphology and distribution will be assessed by electron microscopy. This will be an extension of our previous study on hydride precipitation in coarse-grained Zircaloy-2 rod.

The study of Zircaloy has clearly demonstrated that hydride morphology and distribution is partly controlled by the internal grain-interaction stresses. The origin of these stresses is associated with thermal and plastic anisotropy of zirconium.

8.1.2 ***Materials Characterization***

Continue the microstructural evaluation (texture, dislocation density and grain size) of offcuts from fast and slow elongating pressure tubes. Evaluate variation of texture and dislocation density along the length and around the circumference of a standard Darlington tube H1887.

8.1.3 ***High Fluence Deformation of Pressure Tubes***

Continue irradiation of 42 growth specimens and 7 creep capsules at 280°C in the Trillium 2 insert in the French Osiris Reactor. Begin irradiation of 42 growth specimens and 7 creep capsules at 310°C in the Trillium 3. Continue the investigation of the microstructures of surveillance tubes and irradiation growth specimens by analytical and transmission electron microscopy. Assess the effect of temperature changes on long-term growth rates. Coordinate the preparation of a detailed report of the Dido experimental program which will be written by the Harwell staff who had responsibility for the program. Assess the effect of a post-irradiation anneal on the microstructure of pressure tube material.

Complete the third phase of irradiation of mechanical test specimens in the Trillium 1 insert. Carry out the third change-out of specimens in the upper part of the insert. Commence the forth phase of irradiation. Conduct mechanical tests on the 18 test specimens (6 cantilever, 6 compact tension and 6 tensile) which were removed from Trillium 1 insert during the first and second specimen change-outs.

Commence out reactor creep tests of biaxial and uniaxial creep specimens machined from standard Darlington tube H1587.

8.1.4 ***Evaluation of Power Reactor Fast Fluxes***

Contract work on a jig to manufacture bundles with irradiated specimens will be completed. Some specimens from Bundle #2 will be tested. These results will be compared with results for similar specimens irradiated in test reactors. A preliminary assessment will be made of the relative effectiveness of the power reactor and test reactor fluxes. The gamma fields of specimens to be recycled will be monitored to establish the recycling schedule.

8.1.5 ***Modelling***

During 1990, the user base of CDEPTH increased to more than 20 people working in different Divisions of Ontario Hydro and at AECL, Hydro Quebec and NB Power. CDEPTH is being used to model an ever widening range of problems, and as a result, users are putting increasing demands on the program. This requires that CDEPTH and its utilities be supported and maintained, and from time to time, modified or extended to enable them to handle new applications.

Work Planned for 1991:

1. Modify CDEPTH as follows:

a) include a RETUBE option,
b) include the effects of thermal strains and stresses,
c) add time-varying boundary loads,

d) make the contact stiffness a function of the length of contact.

2. Use item (d) above to determine the value of contact stiffness required to match the results of CDEPTH with those obtained from the 3-dimensional contact algorithm.

3. Modify PRECD, PLOTC and POSTC to accommodate the new features of CDEPTH.

8.1.6 *Modification of CDEPTH for On-Line SLAR*

This project has expanded to encompass the SLAR and SLARette operations at Gentilly and Point Lepreau. CPS and NED would like the Phase 1 program to be documented and accepted independently as a reactor maintenance tool. The main part of this project is scheduled to be completed in the first half of 1991, with further work on customizing for additional reactors to continue into subsequent years.

Work Planned for 1991:

1. Customize Phase 1 for Bruce-3, Gentilly-2 and Point Lepreau.
2. Complete Phase 2 of the project and customize for B3 and G2.

8.1.7 *Analysis of Reactor Data*

Our previous analyses of fuel channel sag, diametral expansion and contact have contributed to the development and evaluation of design equations, as well as to planning and execution of maintenance operations. This work will continue in 1991. Work on developing the new design equations is under way, and a plan has been suggested by the Design Equation Review Committee for division of labor between various interested parties.

Work Planned for 1991:

1. Develop a methodology for quantifying the agreement of calculated and measured deformation profiles.

2. Extend the database of contact to include all measurements in P4 (1990 and 1991), and Bruce-A units.

3. Complete a study of measured and predicted curvatures in pressure tubes with both sets of design equations.

8.1.8 *Deformation Database*

The importance of OHRD's in-reactor deformation database is becoming evident even before it is officially released. We have already received and fulfilled several requests for data from CPSD, NED (D&D-Gen.) and AECL. The database is also going to be an integral part of the development of a new set of design equations for the pressure tube and the calandria tube.

Work Planned for 1991:

1. Complete a final evaluation of the accuracy of current data, and issue the database, with accompanying documentation.

2. Maintain and extend the database as new data becomes available, and retrieve as much of the old gauging and operating conditions data as possible.

3. Add elongation data (from NED's elongation spreadsheets) to the database.

8.2 ***Development and Application of Specialized Techniques for Mechanical and Physical Property Measurements***

8.2.1 ***Development of Techniques for the Nondestructive Evaluation of Hydrogen in Zirconium Pressure Tube Material***

The work program for 1991 will encompass the following:

(1) Continued development of calorimetry especially in the area of differential measurements for corrosion applications.

(2) Final development and testing of the externally heated resistivity system.

(3) Resistivity measurement of P3 rings.

8.2.2 ***Materials Properties and Biaxial Deformation Behaviour for CANDU Reactor Zircaloy-4 Fuel Cladding at Elevated Temperatures in Air and Steam Environments***

The main objective of this program is to increase the available data base for hydrogen uptake, oxidation kinetics and biaxial deformation behaviour for Zr-4 fuel cladding in air and steam environments.

Work Planned for 1991

1. Carry out tests to delineate more quantitatively the effect(s) of grain morphology and grain size in the starting material on the nature of hydrogen absorption and oxidation kinetics in air and flowing steam environments.

2. Assess the effect of transient oxidation on hydrogen absorption and oxidation kinetics in air and flowing steam environments.

3. Utilize the most current Zr-4 materials data to produce updated criteria for failure and "handling" of air and steam oxidized Zr-4 fuel cladding material.

4. Perform appropriate mechanical tests, hydrogen analysis and metallurgical examinations to obtain the relevant materials data.

8.2.3 ***Special Studies***

The main objective of this program is to maintain and augment the test techniques and test facilities that have been developed for materials testing in support of the Section's various R&D programs, in particular, and Ontario Hydro's programs in general.

Work Planned for 1991

1. Improve and augment existing test capabilities.

2. Develop new experimental techniques and associated hardware and software when the need arises.

3. Carry out more comprehensive compression testing of Zr-2.5 Nb PT material at both ambient and elevated temperatures.

4. Carry out more comprehensive stress relaxation testing of Zr-2.5 Nb PT material.

8.3 *Pressure Tube Fabrication*

8.3.1 *Modified Pressure Tubes*

The main objective of this program is to develop a more fundamental understanding of the factors which control the formability of Zr-2.5 Nb pressure tube material so that metal working processes used in fabrication can be optimized for new or modified pressure tube types.

Work Planned for 1991

1. Set up a test facility at OHRD whereby small pressure tube extrusions can be cold drawn under various conditions to investigate the impact/effect of altering process parameters on tube fabricability and tube quality.

2. Develop the required test procedures and ancillary equipment needed for cold drawing of small pressure tube extrusions.

3. Develop further the test techniques for generating basic materials data for Zr-2.5 Nb pressure tube material.

4. Develop further the work on development of mathematical and/or finite element models suitable for use in the analysis of metal forming processes relevant to pressure tube fabrication. The bulk of this modelling work will be done in collaboration with researchers at the University of Toronto.

9.0 *ADVANCED INDUSTRIAL MATERIALS*

9.1 *Expert Systems to Diagnose Material Problems*

The main objective of this program is to make computer accessible information on materials selection, performance and maintenance.

Work Planned for 1991

1. Continue to develop expert systems building technology.

2. Assist power station personnel with implementation of existing and newly developed expert system for materials performance maintenance.

3. Develop site specific expert system for Bruce Heavy Water Plant for recognition and diagnosis of materials problems.

9.2 *Coatings*

Work will continue on a Director's Fund Project to identify material property improvements possible by laser treatment of plasma sprayed coatings for use in advanced energy systems. Emphasis will be to develop coatings more resistant to the environment in the gasification portion of an IGCC plant. The project is a joint effort with the Metallurgy Section and Electrical Research Department. Tasks to be completed during 1991 include a literature review to select materials, fabricate test coupons and establish a test design.

From the literature survey into gas turbine materials it is clear that research initiatives should be pursued to develop improved coating formulations and

application techniques for high temperature components. It is envisioned that a thermal cycling test rig will be used to test coated material components in simulated service environments. Creep testing and metallographic studies will also be required to assess and compare degradation types and rates involving the several classes of alloys currently available. Refinement of welding repair techniques are needed, particularly for mechanically alloyed, oxide dispersion strengthened alloys. The efficacy of hot isostatic pressing for repair of creep cavitation damage should be further explored.

9.3 ***Advanced Materials Use in Transmission and Distribution Lines***

The main objective of this program is to identify specific opportunities and define work programs to address materials related problems and meet increased performance requirements.

This will be achieved through on OHRD Working Group set-up to develop multidisciplinary/interdepartmental programs.

Work Planned for 1991

1. Complete the development of research programs addressing materials problems and increased performance requirements.

2. Initiate research programs to implement advanced materials into the power transmission and distribution system.

9.4 ***Overhead Line Components***

The main objective of this program is to optimize properties of commercially available aluminum-silicon carbide (Al-SiC) composites to significantly exceed currently specified materials. This work will be done in cooperation with CANMET and Brampton Foundries Inc.

The overhead transmission life assessment program revealed that the life limiting mechanism was corrosion of the galvanized steel core wires. These are necessary to provide high strength mechanical support for the surrounding cold drawn aluminum conductor wires particularly during moderately elevated temperature operation. If the conductors could be made stronger and more creep resistant without significant loss in conductivity and corrosion resistance then the failure prone core wires could be dispensed with. Contact has been made with a producer of continuously cast wire products. It is hoped that the potential for an aluminum metal matrix composite can be explored for creep resistant conductor applications.

9.5 ***Canadian Electrical Association Studies - Advanced Materials Use in Transmission and Distribution System***

The objective of these studies is to review transmission and distribution line problems, identify those related to materials and develop approaches to resolve these materials through implementation of advanced materials.

9.6 ***Aluminum Castings***

Research activity will continue on the CEA 300-T-689 aluminum alloy castings program. Fracture mechanics and fatigue tests will demonstrate levels of materials properties made possible by recourse to optimal foundry practice and compare them with the unacceptable results of conventional techniques.

9.7 *Failure Analysis*

It is anticipated that we will continue to provide technical services as required to the operating and design units of Ontario Hydro. Demand for such service remains high and will probably utilize 50 to 60% of available man-hours. The current backlog in this area of activity consists of twelve jobs ie, approximately three months work.

Approved by:

J. Brown
Manager
Metallurgical Research Department

Prepared by:

R.G. Fleck
Supervising Engineer
Materials Technology Section

REPORTS

89-2-K	Creep Response of Fuel Channels in CANDU Nuclear Reactors: Computer Code CDEPTH, Version 6 *R.G. Sauve and N. Badie*
89-35-P	Model for the Spread of Contact Between Pressure Tube and Calandria Tube *R.A. Holt and N. Badie*
CEA Contract No. 112-G-277	Treatment to Prevent Exfoliation of Tube Bores *P. Mayer and A.V. Manolescu*
90-66-K	"CORUND" - Expert System for Diagnosis of Corrosion Problems in Buried Power Distribution Systems" *P. Mayer*
90-67-K	Characterization of Y-Ba-Cu-O High Temperature Superconductors *P. Mayer*
90-117-K	COREC-Expert System for Recognition and Identification of Forms of Corrosion Attack *P. Mayer*
90-186-P COG 90-101	Microstructural Studies in Support of COG Research Programs *R.G. Fleck*
90-248-P COG 90-153	Effects of Internal Grain-Interaction Stresses on Hydride Precipitation in Zircaloy *V. Perovic, S.R. MacEwen, G.C. Weatherly, M. Leger*
M90-19-K	Creep Testing on a Lakeview Main Steamline Weldment *E.T.C. Ho and H.J. Westwood*
M90-21-K	Circumferential Cracking in End Ring Fitting Areas of Generator Rotors - Nanticoke GS *G. Bellamy*
M90-22-K	Failure of a Bleed Condenser Gasket and Leak-Off Line Unit 2, PNGS "A" *G. Bellamy*
M90-26-K	Condition Monitoring and Life Assessment on Tower Structural Steel from the 115 kV Line K7B/K8B *G. Bellamy*
M90-29-K	Condition Monitoring on Overhead Conductor Materials *G. Bellamy*
M90-31-K	Failure of a Lightning Arrestor Tower on the Unit 3 Reactor Building PNGS *G. Bellamy*
M90-34-K	Corrosion and Wear on Headgate Wheel and Axle Assemblies *G. Bellamy*
M90-35-K	Fracture of Lube Oil System Springs PNGS A *G. Bellamy*

REPORTS *(Cont'd)*

M90-36-K	Leakage of a Copper Tubed Building Heater Atikokan TGS *G. Bellamy*
M90-37-K	O.D. Surface Wall Thinning on the Unit 6 Bleed Condenser Tubes BNGS B *G. Bellamy*
M90-42-K	Inert Atmosphere Creep Testing of Subsize Creep Specimens *M. McGraw*
M90-44-P	Failure of Safety Devices on a Heavy Duty Ladder York Hydro *G. Bellamy*
M90-48-K	Suspension Leaf Spring Failure on a Single Axle 9900 kg Pole Semi-Trailer T&WE *G. Bellamy*
M90-49-K	Failure of a L.P.S.W. Pump Motor Bearing, Unit 2, BNGS A *G. Bellamy*
M90-50-K	Failure of an Induced Draught Fan, Unit 1, Lennox TGS *G. Bellamy*
M90-51-K	The Quality and Consistency of Post Seals in Lead-Acid Standby Power Cells, Darlington NGS *G.Bellamy*
M90-52-K	The Quality and Consistency of Post Seals in Lead-Acid Standby Power Cells Darlington NGS *G. Bellamy*
M90-54-K	Corrosion of Cemented Carbide Mechanical Seal Faces from Water Systems Pumps - Darlington NGS *J. Noga*
M90-56-K	An Evaluation of Cast Aluminum Alloy Duckbill Grounding Clamps *G. Bellamy*
M90-57-K	Flexible Hydrogen Transfer Hose Failure BNGS A *G. Bellamy*
M90-63-K	ASTM A757 E2-Q1 Alloy Steel Casting for Optical Skywire Deadend Applications *G. Bellamy*
M90-64-K	Repetitive Fracture of Compressed Air Line Fittings *G. Bellamy*
M90-71-K	An Experimental Procedure for the Nucleation and Growth of Axial ID-Initiated Cracks in Sections of Zr-2.5 wt% Nb Pressure Tube Samples *E.T.C. Ho and M.J. McGraw*
M90-73-K	Fracture of the Master Link on the No. 2W Fuelling Machine Elevator, Unit 2, PNGS A *G. Bellamy*

REPORTS *(Cont'd)*

M90-76-P	Trillium 2 - Overview *J.E. Elder*
M90-78-P	Failure Analysis on Ottawa Hydro Vehicle 87-12. *G. Bellamy*
M90-79-K	Split Aluminum Alloy Tubing Guide Analysis, NK38-DOH-60608-9003, Unit 3, Darlington NGS *G. Bellamy*
M90-82-K	Loosening and Fracture of Rim Support Bolts, Arnprior GS *G. Bellamy*
M90-85-P	Trillium-2 Creep Capsule Dimensioning Results After the Second Irradiation Period *J.E. Elder*
M90-86-K	Brittle Fracture of LPSW Non-Return Valve 6-7131-NV206, Unit 6, PNGS *G. Bellamy*
M90-87-K	Premature Failure of Brush Contact Springs in Hydraulic Generation Service. *G. Bellamy*
ME90-5-H	Effect of Annealing on the Ultimate Tensile Strength of ASTM B230 Cold Drawn Aluminum Alloy 1350-H19 *G. Bellamy*
ME90-6-K	Fracture of Reed Elements in an Annulus Gas Compressor Valve - Darlington NGS *G. Bellamy*
ME90-7-K	Fracture of Stainless Steel Socket Head Screws on a Unit 4 Paddle Gland LVGS *G. Bellamy*
ME90-8-K	Failure of a Temporary Steampipe, Darlington NGS *G. Bellamy*
ME90-9-K	ASTM A193 Gr. B7 Stud Bolts for BNGS 'A' *G. Bellamy*
ME90-10-H	Dulmison Cast Aluminum Alloy Transmission Components *G. Bellamy*
ME90-11-K	Structural Aluminum I-Beam from Ear Falls GS *G. Bellamy*
ME90-13-K	Generator Rotor Lug Cracking, Nanticoke TGS *G. Bellamy*

CONFERENCE/SEMINARS AND TECHNICAL MEETINGS

Visit CRNL to discuss COG programs, January 16-17, 1990.
R.A. Holt

Visit Nu-Tech in Arnprior, Ontario to discuss with S.A. Aldridge pressure tube fabrication processes, January 22-23, 1990.
E.T.C. Ho

Visit CRNL to discuss COG Programs, January 25-26, 1990.
R.A. Holt

Electrotechnologies and Industry - CCE Congress 90, Calgary, Alberta, April 2 & 3, 1990.
J.O. Noga

Canadian Advanced Industrial Materials Forum, Board of Directors Meeting, Toronto, Ontario, April 6, 1990.
P. Mayer

Microstructural Meeting at AECL-CRNL, April 11, 1990.
R.G. Fleck and N. Badie

Working Party #32 Meeting, AECL-CRNL, April 12, 1990.
R.G. Fleck

National Association of Corrosion Engineers, Annual Meeting, Las Vegas, Nevada, April 23-26, 1990.
P. Mayer

NACE-MTI-EFC Joint Workshop on Expert Systems, Las Vegas, Nevada, April 27-28, 1990.
P. Mayer

3rd Canadian Conference on High Temperature Superconductivity, McGill University, Montreal, Quebec, May 4-5, 1990.
P. Mayer

Workshop on Applications of Metal Matrix Composites, CANMET, Ottawa, Ontario, May 9, 1990.
P. Mayer, J.O. Noga

2nd Symposium/Workshop on Applications of Expert Systems, Royal Military College, Kingston, Ontario, May 10-11, 1990.
P. Mayer

CANMET, Ottawa, Ontario, May 16, 1990.
R.G. Fleck

Saclay, Paris, France, June 11-15, 1990
R.G. Fleck

International Standards Organization, TC156, Boston, Massachusetts, June 11-15, 1990.
P. Mayer

Texture Workshop, Kingston, Ontario, June 19, 1990.
J. Elder

CONFERENCE/SEMINARS AND TECHNICAL MEETINGS (Cont'd)

2nd Canadian Materials Science Conference, Royal Military College, Kingston, Ontario, June 19-22, 1990.
P. Mayer

Creep and Growth Technology Course (Joint Hydro-AECL), Oakville, Ontario, June 22, 1990.
N. Badie, J. Elder, S. Perkons

Canadian Advanced Industrial Materials Forum, Board of Directors Meeting, Edmonton, Alberta, June 25, 1990.
P. Mayer

Alberta Research Council, Edmonton, Alberta, June 26, 1990.
P. Mayer

PLP Cleveland, Discuss design of new line hardware, July 5, 1990.
G. Bellamy

Westinghouse, Hamilton, Confer on gas turbine materials, July 17, 1990.
G. Bellamy, R.G. Fleck, J. Noga, C.J. Simpson

FUNK Finecast, Columbus, Ohio. Discuss line hardware casting, July 26, 1990.
G. Bellamy

Visit to AECL-CRNL, discussion of irradiation program at Harwell with R.A. Holt, B. Sheldon, R. McElroy, July 31, 1990
N. Badie, R.G. Fleck

Meeting on carrier bundle program with T. Gendron, I. Oldaker, August 1, 1990.
N. Badie

Meeting on CDEPTH and computational efforts with A. Causey, August 1, 1990
N. Badie

Conference on defects in hexagonal close-packed crystals; International Centre for Theoretical Physics, Trieste, Italy, August 17-17, 1990
V. Perovic

ALTEC, Milton - discuss failure of hydraulic manlifts, August 16, 1990
G. Bellamy

COG Microstructural Studies at AECL-CRNL, August 27, 1990.
R.G. Fleck, L.M. Brown

CIM Conference, Hamilton - Chair retrospective design session, August 27, 1990.
G. Bellamy

Meetings on Trillium experiments and X-ray diffraction at AECL-CRNL, September 6, 1990.
J. Elder

OCMR Composites Workshop, Toronto, Ontario, September 6, 1990
J.O. Noga

CONFERENCE/SEMINARS AND TECHNICAL MEETINGS (Cont'd)

Visit McMaster University - discuss the work on the effects of internal grain-interaction stresses on hydride precipitation in zircaloy with Prof. G.C. Weatherly, - Discuss the project on microstructural and microstructural studies of Zr-Nb alloys with Prof. G.R. Purdy, September 14, 1990.
V. Perovic

Seminar on the microstructure of pressure tubes at AECL-CRNL, September 24, 1990.
J. Elder, V. Perovic

WESTAIM/Sherritt Gordon Ltd., Fort Saskatchewan, Alberta
P. Mayer

Attend annual review meeting for COG WP33 at CRNL, October 4, 1990.
E.T.C. Ho

Canadian Advanced Industrial Materials Forum, Board of Directors Meeting, Dupont Co. Inc., Mississauga, Ont., October 11, 1990.
P. Mayer

Attend annual review meeting for COG WP9 at Sheridan Park, November 20, 1990.
E.T.C. Ho

Paris, France - Meeting at CEA Saclay on the Trillium Experiments, Petten, Holland - Meeting regarding the start-up of an in-reactor experiment, November 26-30, 1990.
J.E. Elder/R.G. Fleck

Fuel Channel Data Workshop at Sheridan Park, November 27, 1990.
S. Perkons/N. Badie

Ninth International Symposium on Zr in the Nuclear Industry, Kobe, Japan, November 3-7, 1990
K. Tashiro

International Standards Organization Meeting of Technical Committee #156, Working Group #9, Moscow, USSR, November 19-23, 1990.
P. Mayer

Metallurgical Society of CIM Program Meeting, Montreal, Quebec, December 7, 1990.
P. Mayer

IREQ, Meeting on CEA Study 333, Varenes, Quebec, December 7, 1990.
P. Mayer

CSA Committee on Galvanizing of Steel, October 10, 1990.
G. Bellamy

PRESENTATIONS AND PUBLICATIONS

Diagnostic Expert System for Boiler Tube Failure Analysis
Presented at Seminar at McMaster Corrosion Centre, Hamilton, Ontario, April 2, 1990
P. Mayer

'CORUND' - Expert System for Diagnosis of Corrosion Problems in Buried Power Distribution Systems" -
Presented at CORROSION 90, Las Vegas, Nevada, April 24, 1990.
P. Mayer

High Temperature Superconductor/Metallic Conductor for High Current Applications in Power Systems"
Presented at 3rd Canadian Conference on High Temperature Superconductivity, Montreal Quebec, May 5, 1990.
A.V. Manolescu, P. Mayer, S. Kishnasamy, E. DiBlasio, M. Eygenraam

C-Component Dislocations in Sub-boundaries in a Zr-2.5 Wt% Nb Alloy.
Published: Journal of Nuclear Materials 174 (1990) 327, July 1990.
V. Perovic, G.C. Weatherly, R.G. Fleck

Boiler Tube Failure Mechanisms Recognition - An Expert System".
Published: Bulletin of Canadian Institute of Mining and Metallurgy, Vol 82, No. 939, July 1990, pg 92-95.
P. Mayer

Behaviour of Steels in Steam.
Presented: Conference of Metallurgists, CIM, Hamilton, Ontario
P. Mayer, A.V. Manolescu

Materials Characterization Techniques for High Temperature Superconductors, (in Italian)
Published: Ceramica Acta, No. 5, September-October 1990, pg 1-15.
P. Mayer, E. DiBlasio, R. Cilic, F.Y. Chu